# Constraining constant and tomographic coupled dark energy with low- and high-redshift probes


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# Contents

# Context/Motivation

The concordance ΛCDM model has been very successful at describing our Universe, yet some questions remain:

- What is the **true nature** of 'dark energy'?
- Why is there a **~5σ tension** between the value of the Hubble constant derived from the Cosmic Microwave Background at high redshifts ($H_0 = (67.4 \pm 0.5)$ km/s/Mpc), and lower-redshift distance ladder measurements ($H_0 = (73.04 \pm 1.04)$ km/s/Mpc)?

**IS THE ΛCDM MODEL SUFFICIENT?**

# Coupled Dark Energy Formalism

- $\Lambda$CDM model extensions typically involve modifying Einstein's Field Equations:

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \boxed{\frac{8\pi G}{c^4} T_{\mu\nu}}$$

- We study a form of a **Coupled Quintessence model**
  - Dark energy takes on the form of a scalar field $\phi$
  - Mediates interactions between dark matter particles — these particles feel a 'fifth force'
  - Mass of DM particles m($\phi$) is dependent on the field

# Coupled Dark Energy Formalism

- In coupled dark energy models, we start from the energy-momentum tensor:

$$\nabla^{\mu} T^{\phi}_{\mu\nu} = \kappa\beta T^{\rm dm} \nabla_{\nu}\phi \quad ; \quad \nabla^{\mu} T^{\rm dm}_{\mu\nu} = -\kappa\beta T^{\rm dm} \nabla_{\nu}\phi \, ,$$

where β quantifies the **coupling strength** between dark matter (DM) and the dark energy (DE field) (in ΛCDM, β = 0)

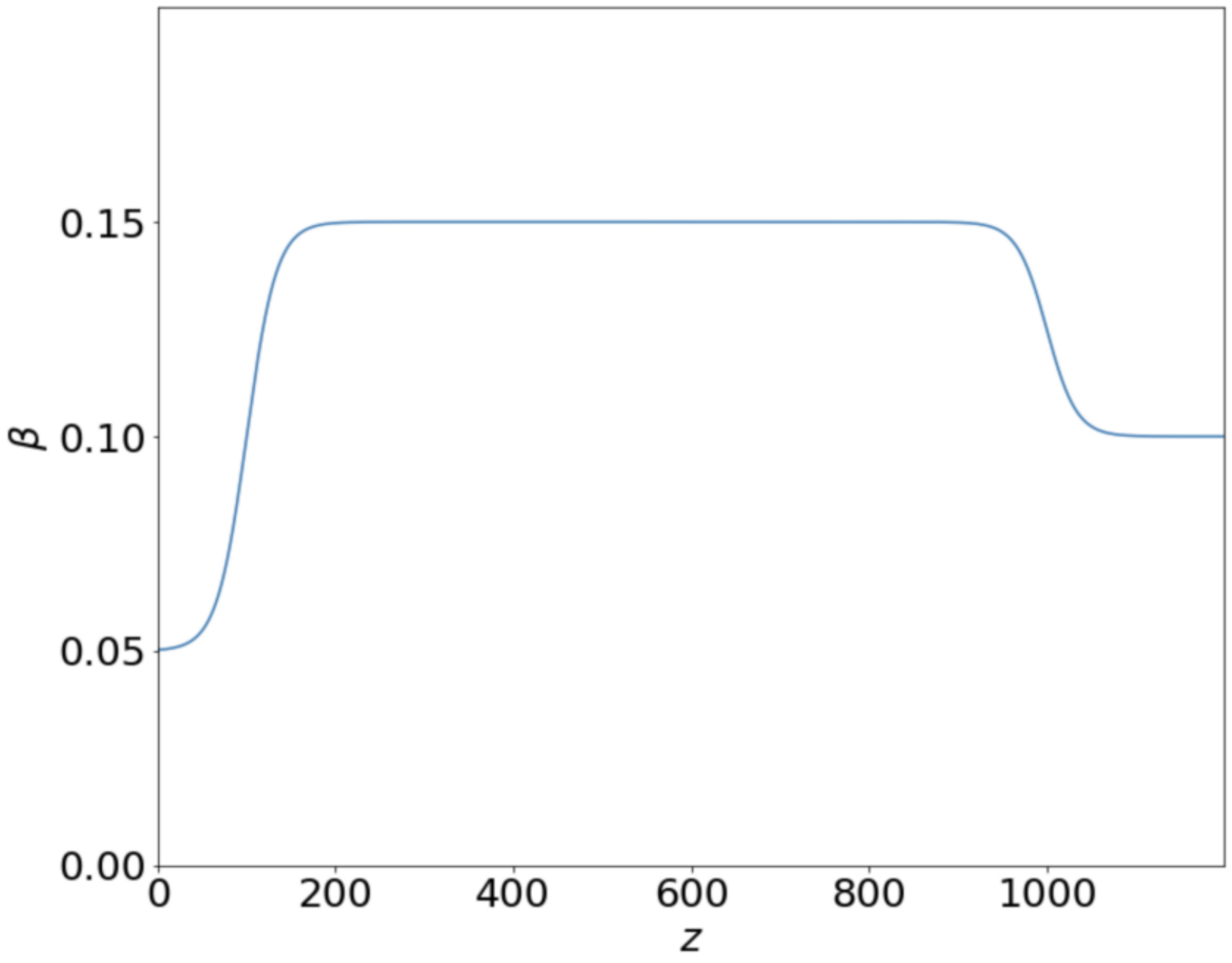
- Coupling strength β has been constrained to be on the order of $\mathcal{O}(10^{-1})$ or less

# Tomographic Coupled Dark Energy

- The case of a constant coupling has been studied substantially in literature
- Here we propose a form of parametrisation for β, where it can **vary with redshift**:

$$\beta(z) = \frac{\beta_1 + \beta_n}{2} + \frac{1}{2}\sum_{i=1}^{n-1}(\beta_{i+1} - \beta_i)\tanh[s_i(z - z_i)]$$

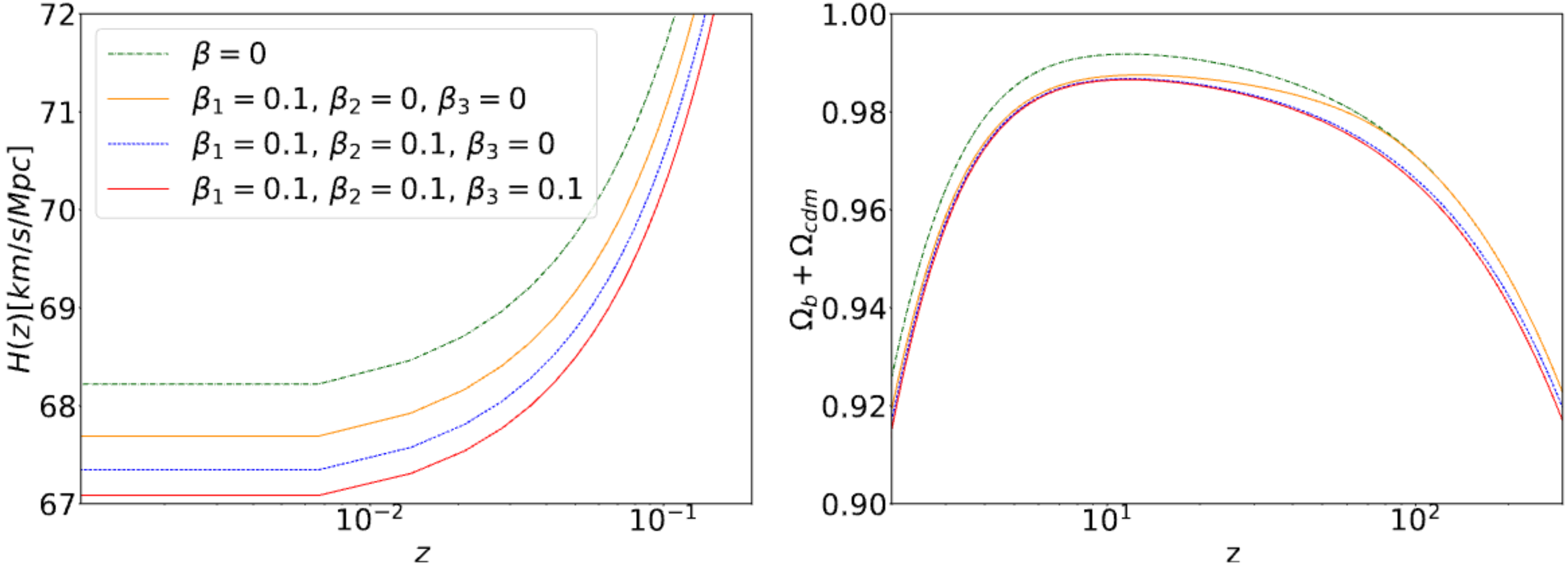
where $\beta_i$ is the amplitude of each tomographic bin and $s_i$ is the smoothing factor between bins



# Tomographic Coupled Dark Energy

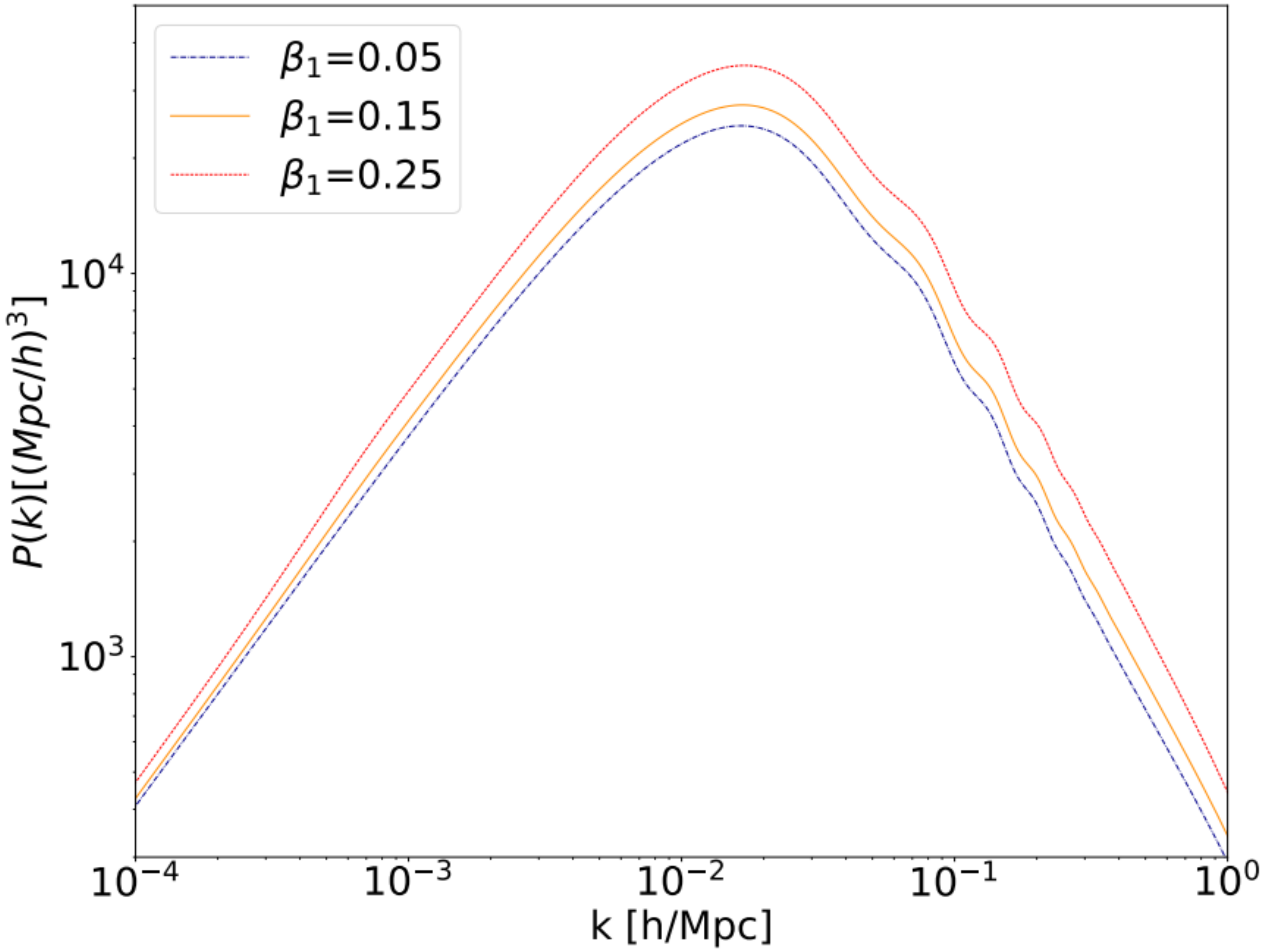
## Physical Consequences

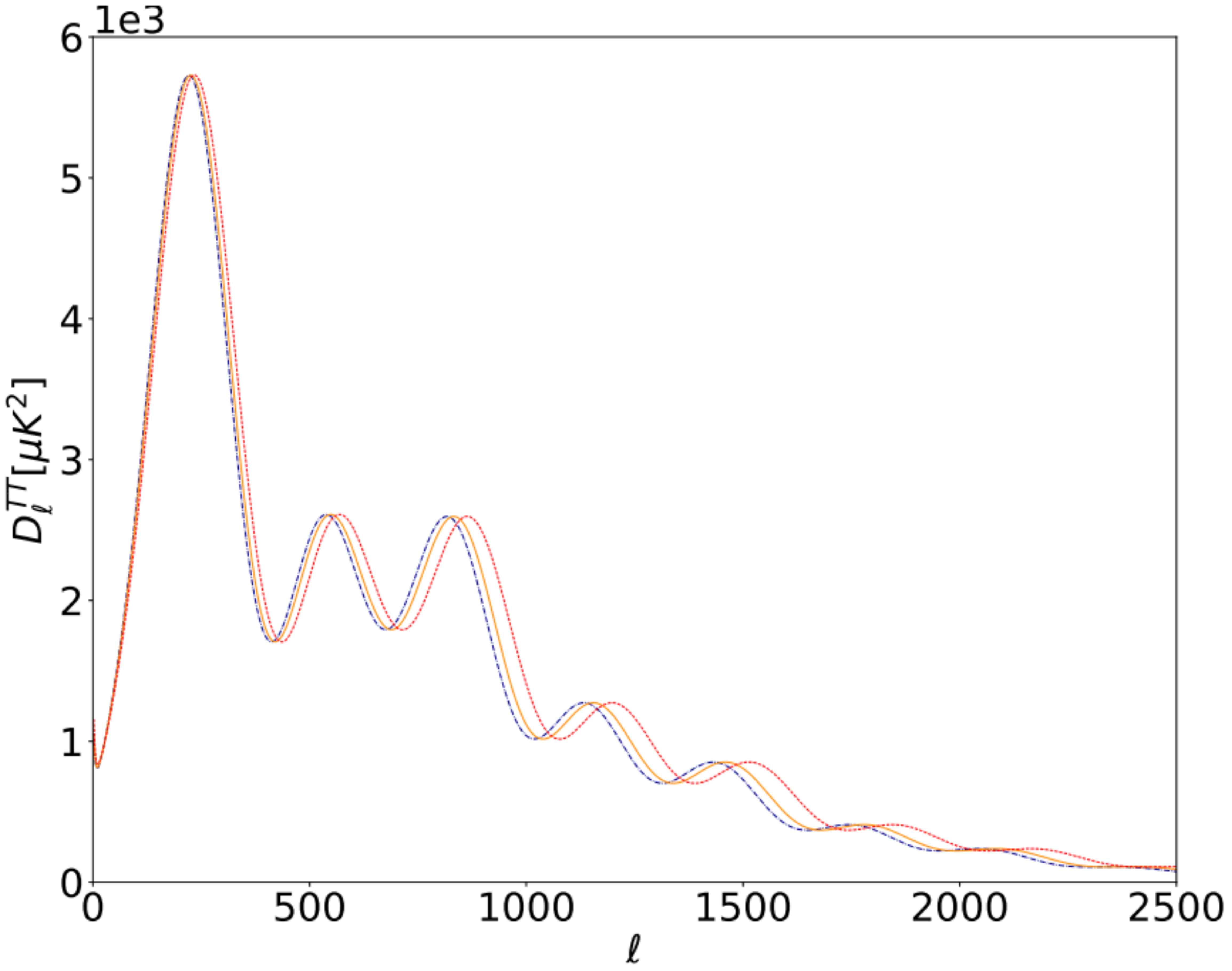
- How do background quantities change?
    - Value of $H_0$ shifts
    - $\Omega_m$ decreases



# Tomographic Coupled Dark Energy

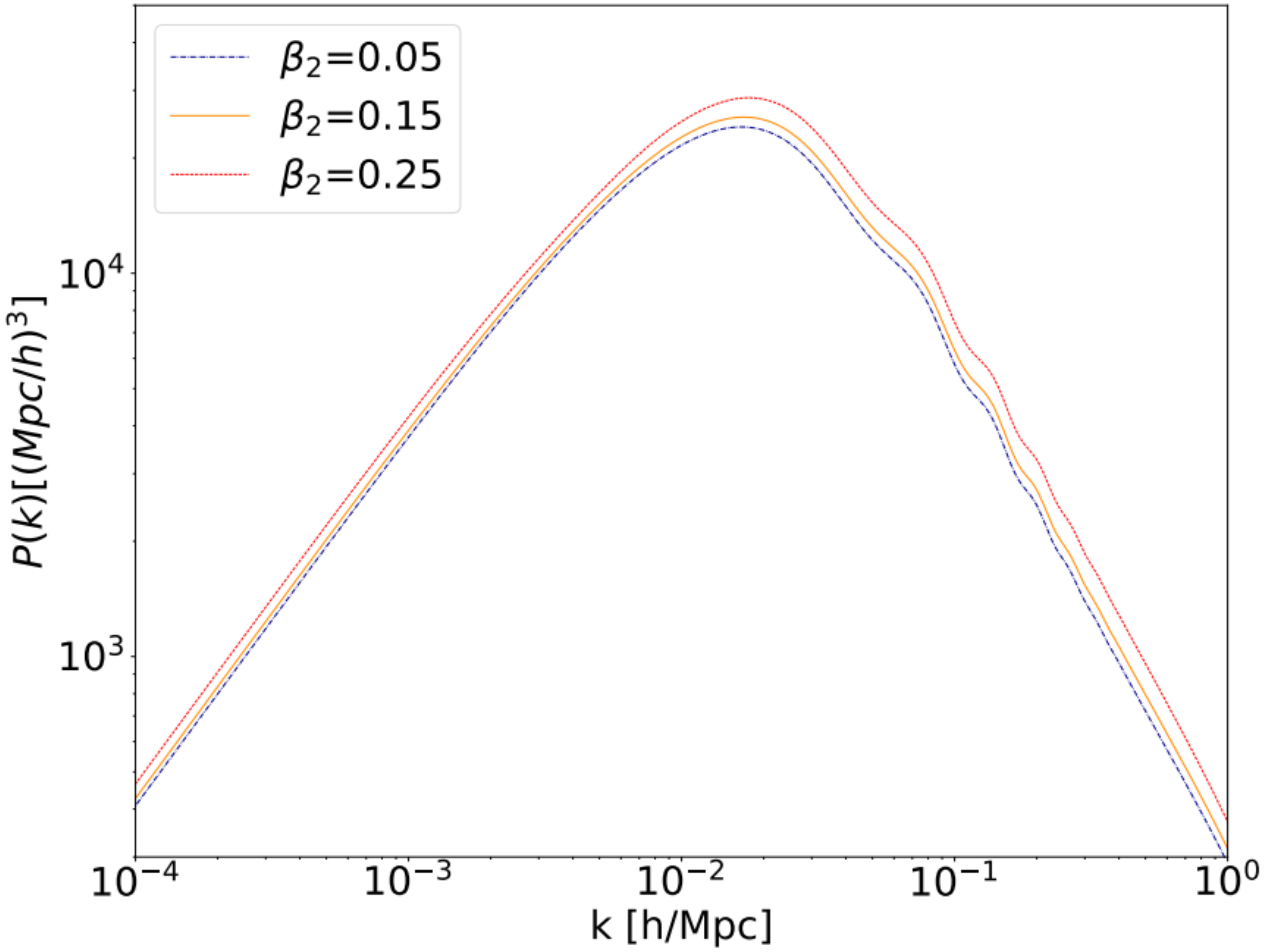
## Physical Consequences

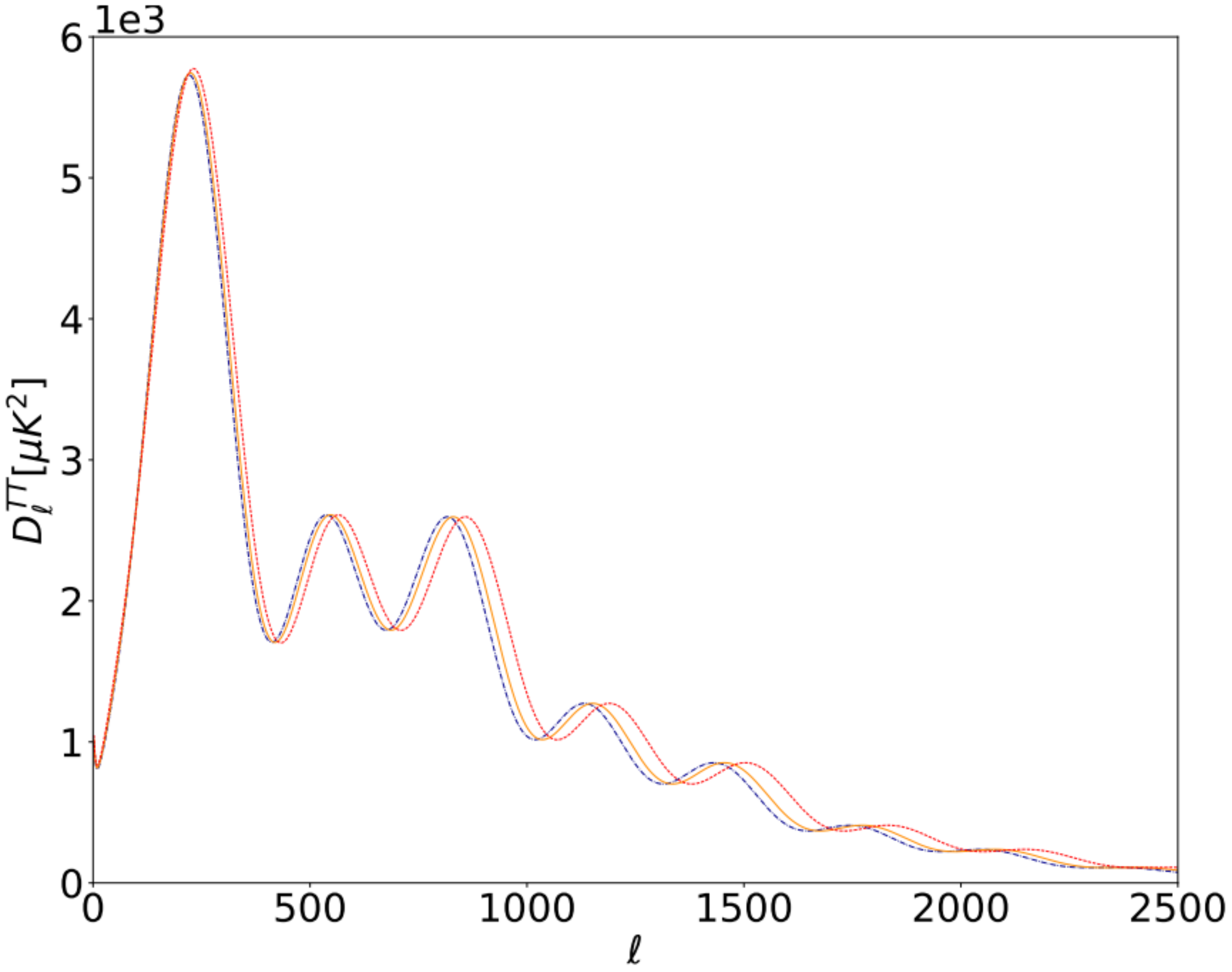


# Tomographic Coupled Dark Energy

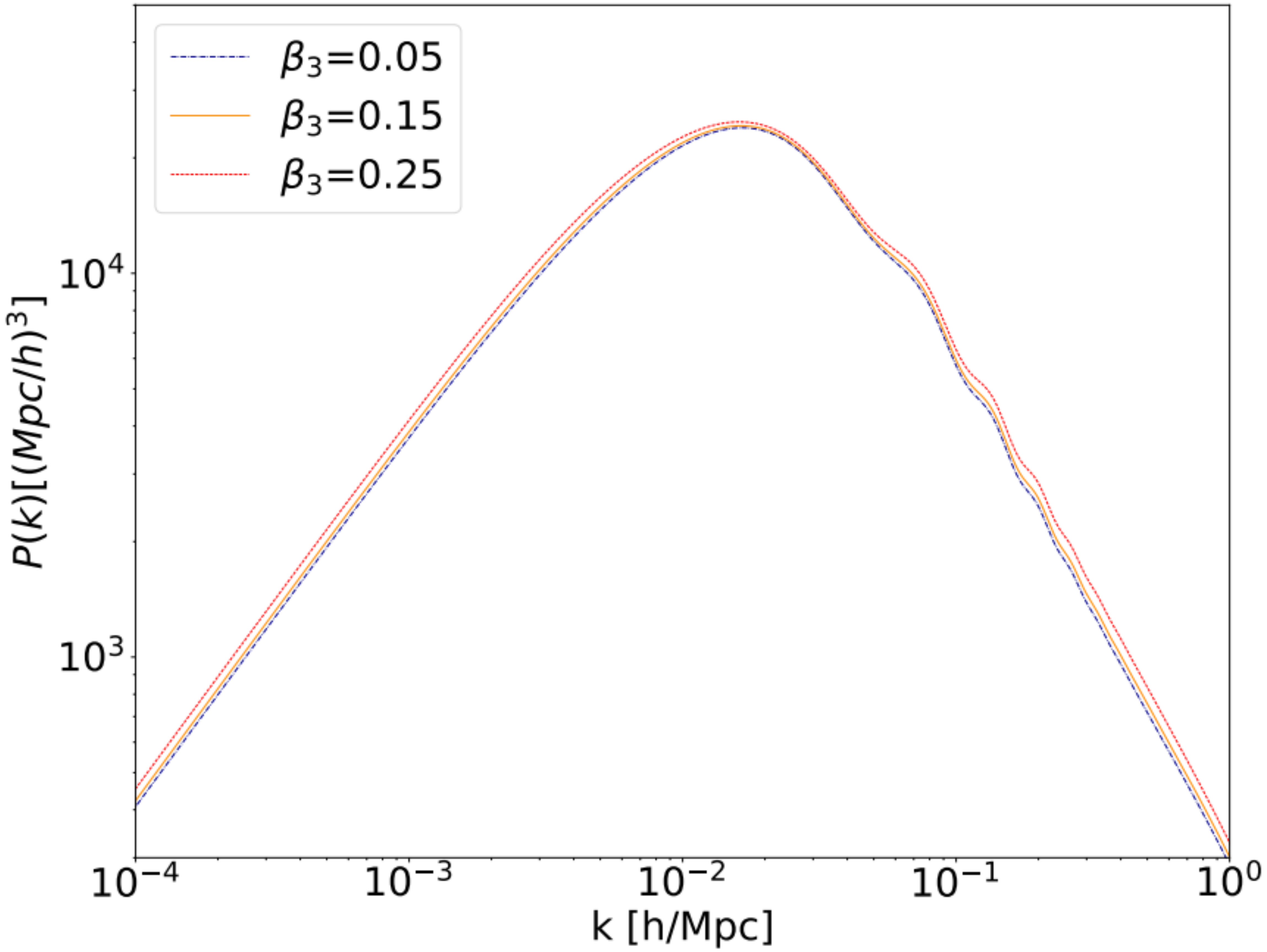
## Physical Consequences

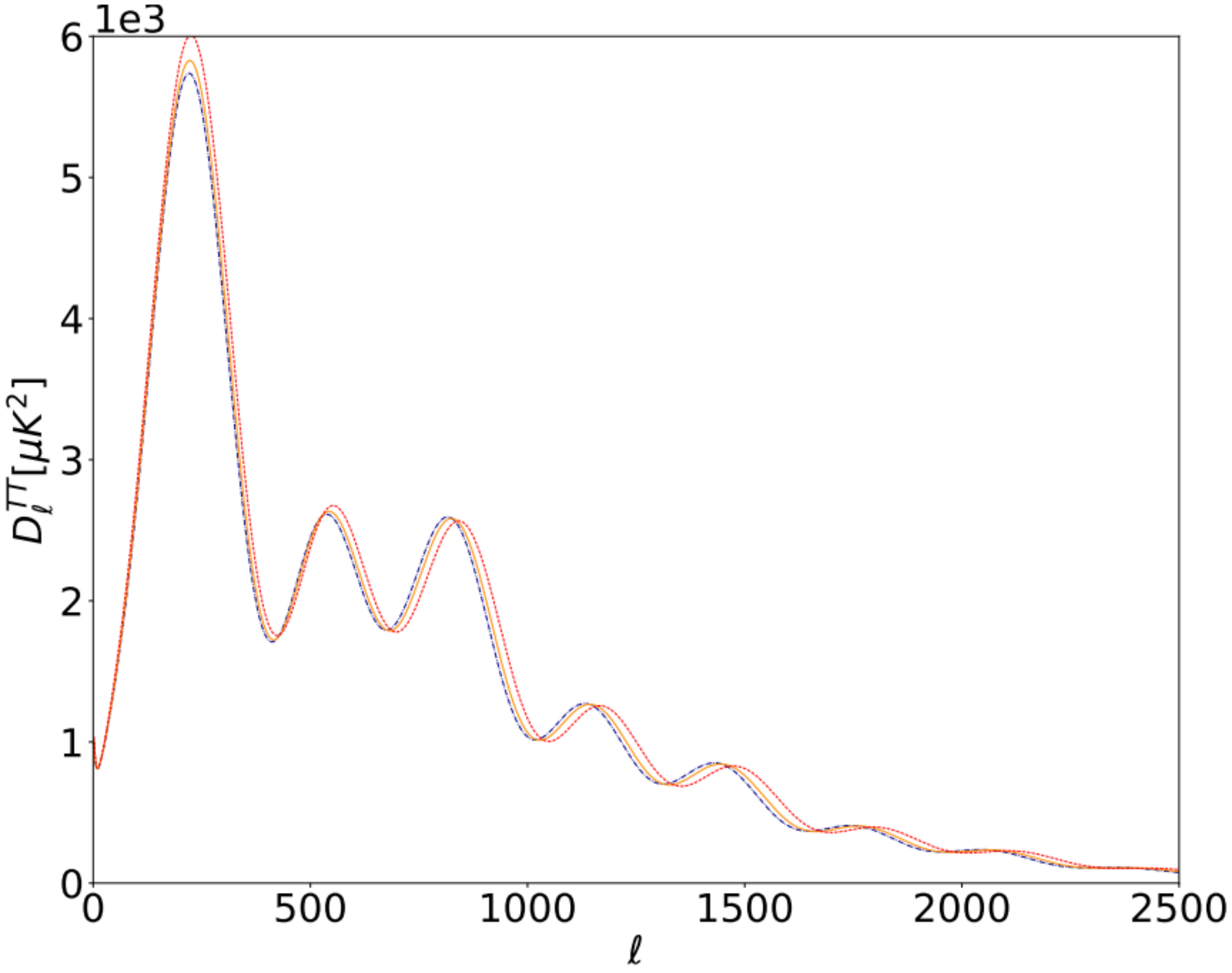


# Tomographic Coupled Dark Energy

## Physical Consequences



# Methodology

## Data

1. **Cosmic Microwave Background**:
    - Planck 2018 TT, TE and EE
    - Atacama Cosmology Telescope (ACT) Data Release 4 TT, TE and EE
    - South Pole Telescope (SPT) TE and EE
2. **Baryonic Acoustic Oscillations** (BOSS, eBOSS, WiggleZ, DES Y3 ): $0.122 < z < 2.34$
3. **Redshift Space Distortions** (BOSS, WiggleZ, VIMOS, SDSS): $0.03 < z < 1.36$
4. **Type 1a Supernovae** (Pantheon, DES Y3 SN)
5. **Cosmic Chronometers** (measurements of H(z) from evolving galaxies): $0.07 < z < 1.905$
6. **SHoES** prior: $H_0 = (73.04 \pm 1.04)\ \mathrm{km/s/Mpc}$
7. **Weak Lensing**: KiDS-1000 cosmic shear, BOSS DR12 spectroscopic galaxy clustering and their 3x2pt

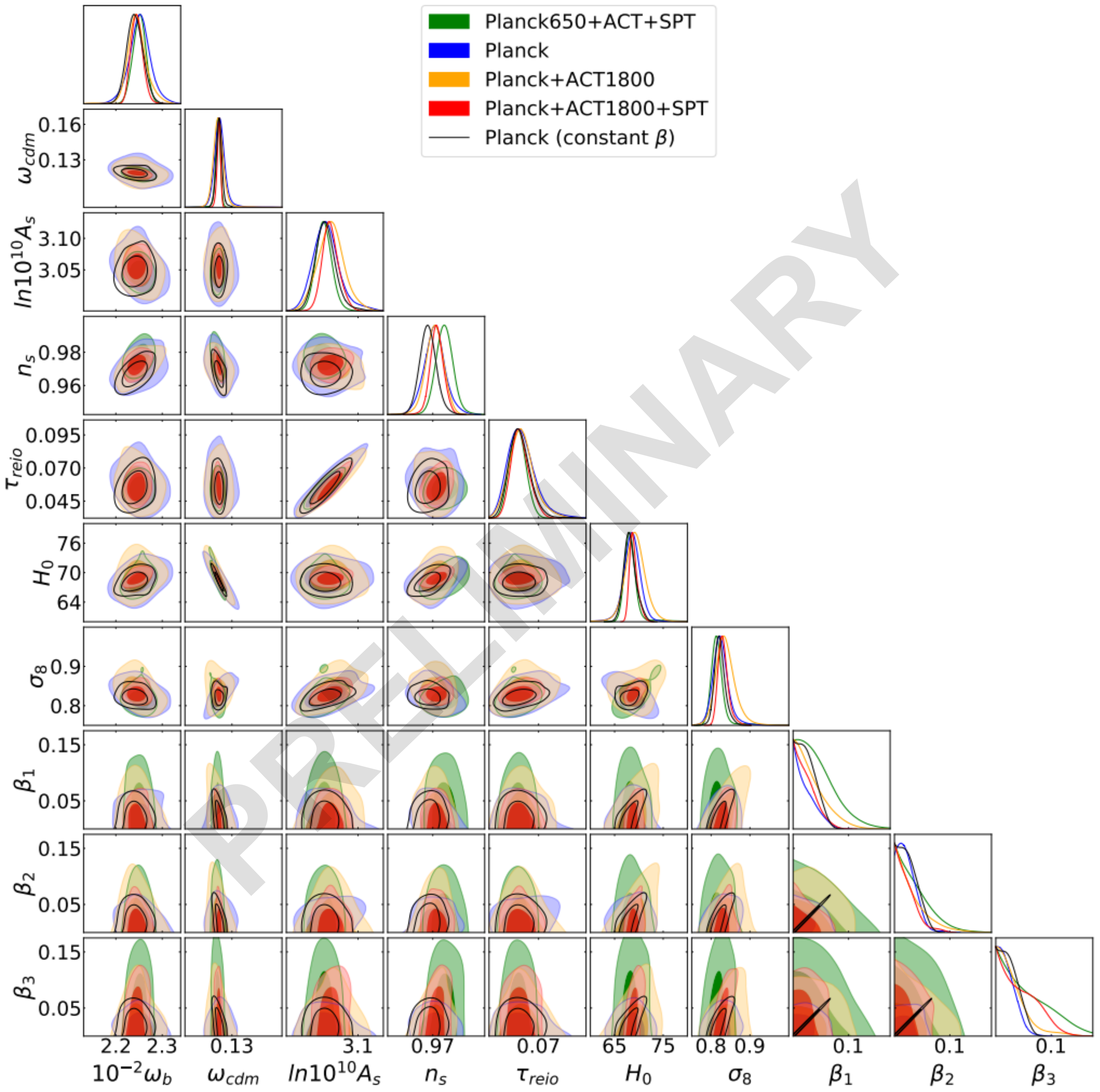
# Methodology

- We modify the Boltzmann solver **Cosmic Linear Anisotropy Solving System (CLASS)** and run Monte Carlo Markov Chains, performing a likelihood analysis to constrain our tomographic coupling model
- How will different combinations of datasets affect constraints on $\beta(z)$?

# Results

**3-bin model with CMB**
**z={0,100,1000}**

- Planck650+ACT+SPT allows for **largest values** of β(z): most of constraining power comes from high multipoles of Planck
- Constraints between Planck, Planck+ACT1800, Planck+ACT1800+SPT rather similar

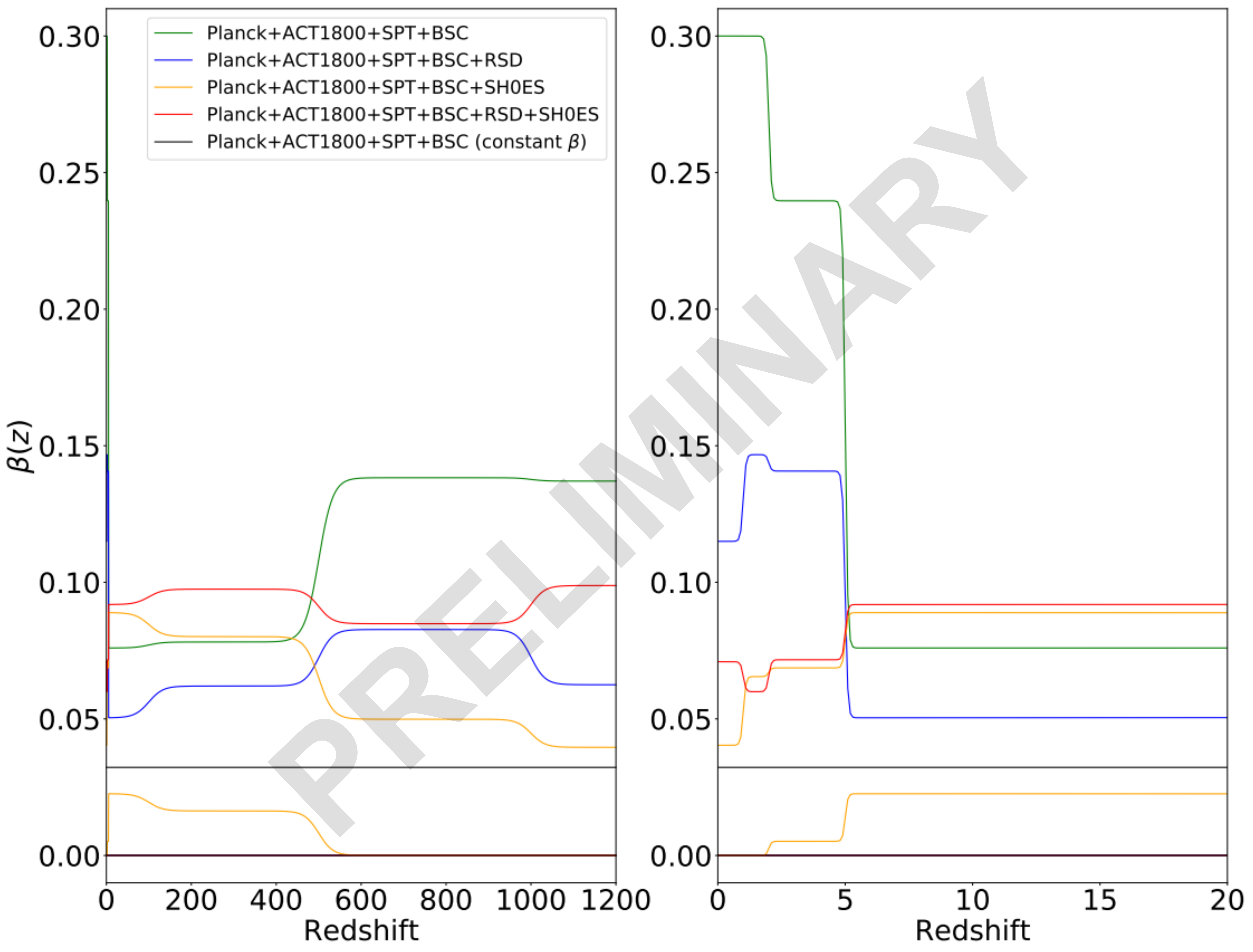


# Results

**7-bin model with BAO+SNe1a+CCH(BSC), RSD, SH0ES**

$z=\{0,1,2,5,100,500,1000\}$

- SHoES prior **favours** $\beta(z) > 0$ at $2\sigma$ level
- This could be due to degeneracy between $H_0$ and $\beta(z)$
- Tightest constraints during **epoch of large scale structure formation** ($5 < z < 500$)

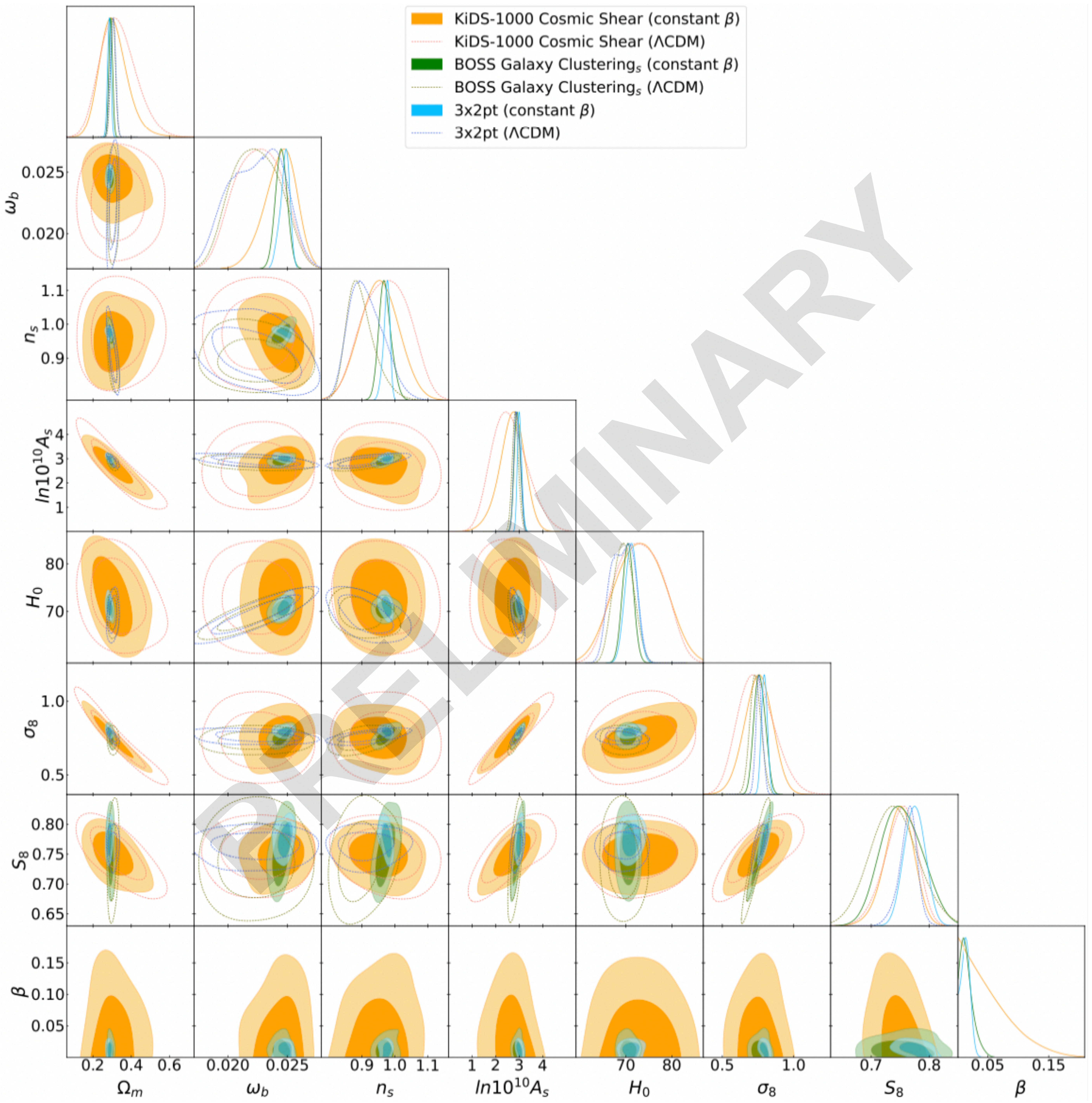


# Results

**Constant Coupling with Cosmic Shear (CS), Galaxy Clustering (GC), 3x2pt**

**z={0,1,1.5,2}**

- Cosmic shear not as effective at constraining coupling: degeneracy in $\sigma_8 - \Omega_m$ plane
- GC and 3x2pt give **very tight constraints**



# Results

**Cosmic Shear, Galaxy Clustering, 3x2pt**

**z={0,1,1.5,2}**


- Also combined weak lensing probes with CMB+BSC: **results closely in agreement with *Planck*,** tension in $S_8$ reduces from ~2.8$\sigma$ to being compatible with *Planck*
- GC and 3x2pt: constraining power comparable with CMB

# Conclusions

- We study a class of CDE models, where **dark energy is a scalar field that mediates interaction between dark matter** particles
- The strength of coupling is quantified by $\beta$, which can be a **function of redshift**
- We test **3 different tomographic binning regimes**, largely motivated by the choice of probes
- A tomographic CDE model **loosens coupling constraints** compared to constant coupling
- With a CMB+CS tension, **tension in $S_8$ is reduced**
- **First time weak lensing and galaxy clustering** used as a probe to constrain coupled dark energy models: showing promising results!

# Thank you!

**Questions?**